Endogenous technology and environmental quality in economic models

den Butter, F.A.G.; Hofkes, M.W.

1998

Faculteit der Economische Wetenschappen en Econometrie

Serie research memoranda

Endogenous technology and environmental quality in economic models

F.A.C. den Butter
M.W. Hofkes

Research Memorandum 1998-58

November 1998

/a/l/e/r/t/

applied
labour
economics
research
team

vrije Universiteit amsterdam

Endogenous technology and environmental quality in economic models

F.A.G. den Butter and M.W. Hofkes*

1. Introduction

The debate on the relationship between the economy and the environment focuses on the question whether there is a trade-off between economic growth and environmental quality. On the one hand it is argued that the increase in production which is a condition for economic growth, enhances pollution and therefore goes at the expense of environmental quality. The counter argument is that economic growth provides the means for investments in abatement activities and for the development of environment saving technology. This would enable a delinking of economic activity and environmental pollution. Moreover, delinking is sometimes interpreted as an increase in preferences for environmental quality as a component of broadly defined economic welfare which goes along with a rise in the level of income.

This debate is essentially about an empirical question which can only be resolved by means of a model based quantitative analysis. In order to enable such quantification it is necessary to integrate the environment into economic models. However, this integration has been hampered by differences in the times scale between economic and environmental developments. Whereas measures of economic policy become effective within a period of say at most four years, for most environmental themes it takes a much longer time period for policy measures to really affect environmental quality. Therefore, the environment can best be integrated into economic models which focus on long-term developments.

From that perspective this article considers the integration of the environment in models of economic growth. According to these models technical progress constitutes a major driving force for economic growth. In the traditional models of economic growth technical progress is exogenous and given as 'manna from heaven'. However, when environmental issues are to be considered within the context of a model of economic growth, it is essential to endogenise technical progress and moreover to endogenise the bias of technical progress. It relates to the

---

* The first author is professor of economics, Free University, Amsterdam, and member of the Scientific Council for Government Policy. The second author is senior economist at the Institute fqr Environmental Studies (IVM), Free University, Amsterdam. This article is part of the research programme "Environmental Policy, Economic Reform and Endogenous Technology: a dynamic policy analysis", funded by The Netherlands Organization for Scientific Research (NWO).

question whether technical progress is neutral, labour saving, capital saving, or 'environment saving'.

The remainder of this article is organised as follows. The next section gives a short survey of the theory of endogenous growth, where, unlike in traditional growth theory, the pace of economic growth may depend on economics of scale in the production process. Section 3 shortly discusses how the concept of sustainable development can be made operational within the framework of models of economic growth. Section 4 gives an example of a theoretical model of endogenous growth which integrates the environment. Section 5 gives an example of an empirical model based on the theory of economic growth. It considers an empirical model built for the Netherlands with endogenous technology and with an energy sector, which forms the connection with environmental issues in the model. Section 6 describes mechanisms of structural change which may be exploited by policy makers in order to enhance environmental quality in a growing economy. Section 7 concludes.

2. Endogenous growth

Neo-classical growth theory originated in the late fifties. The first growth models, as developed by Solow and Swan (Solow, 1956, 1957; Swan, 1956), were characterised by a production function with diminishing returns to the accumulation of capital and constant returns in labour and reproducible capital together. In such a model only continued technological progress can sustain a positive growth rate of output in the long run. Without technological progress the effects of diminishing returns eventually causes economic growth to cease and the only feasible steady-state rate of growth that can result is a zero rate. This unsatisfactory property of neo-classical growth theory has been tackled by new growth theorists, by endogenising the long-run rate of economic growth.

Endogenous growth can be modelled in different ways. In the late eighties the first endogenous growth models appear (Lucas, 1988; Rebelo, 199 1; Romer, 1986). In the so-called AK-model of Rebelo (Rebelo, 1991) endogenous growth arises because of constant returns to the reproducible factors. In this model growth is unintentional but arises as a side product of investment. Romer (1986) extends the neo-classical growth theory by accounting for production externalities. These production externalities are a consequence of knowledge spill-overs in the process of human capital accumulation arising from learning by doing. In the Lucas-model (Lucas, 1988) growth arises from intentional investment in human capital. In this model workers have to decide how much of their time they want to spend on producing goods and how much of their time they use for learning activities. By learning, workers invest in their human capital which leads to higher real wages.

Against the background of these new developments in growth theory there has also been a revival of interest in the integration of the environment in economic models. Standard economic theory does not include the environment as a distinct factor. Nevertheless already in the seventies growth models which include natural resources were analysed. Solow (1974) investigated under which conditions an economy facing limited natural resources could grow forever (see also Stiglitz, 1974). Forster (1973) and Gruver (1976) study the impact of pollution, which arises as an inevitable side-product of economic activity, in the context of Ramsey type growth models. A major shortcoming of these growth models is, however, that the rate of economic growth is determined exogenously.

In the early nineties the first endogenous growth models in which the environment plays a role appear. Gradus and Smulders (1993) analyse two endogenous growth models which incorporate the environment. Their first model is an extension of the AK-model and their second model builds on Lucas (1988). Bovenberg and Smulders (1995) take a step further and develop a growth model with endogenous pollution saving technology which takes the form of knowledge of an efficient use of renewable resources. Hofkes (1996) builds on the Bovenberg and Smulders model and develops a two-sector growth model that also allows for abatement activities. In section 4 this latter two-sector growth model will be described. In the next section we first take a look at the role of sustainable development in model based economic welfare analysis.

3. Modelling sustainable development

Models with endogenous environment can be used for making the concept of sustainability operational in the context of optimal environmental policy. The first step would be to define sustainability within the framework of a theoretical model of economic growth. Following the tradition of welfare economics and that of the theory of economic policy, this framework allows to make a clear distinction between technical and normative (or subjective) elements in the definition of sustainable development. At first sight good candidates for such a definition are:

- an economic growth path with constant environmental capital (or per capita capital in a world with growing population), or
- an economic growth path which results from a dynamic optimisation of a broadly defined welfare function including environmental quality as argument; here an additional restriction (apart from the structure of the economy) may be that environmental capital is constant at the optimal growth path, or that total welfare should not be decreasing over generations.

Technical questions are whether it is feasible, given the functional form of the regeneration process and of the return to investments in environmental capital, to arrive at all at an equilibrium growth path with constant environmental capital or to come to an optimal discounted welfare with the option that also one of the additional restrictions is to hold. Here it should be noted that the latter restriction, namely that total welfare should not decrease over generations can be less binding than the restriction (or sustainability definition) of constant environmental capital. It is the case when an increase in other arguments in the welfare function compensates the decrease in intergenerational environmental quality.

The normative component relates to the desired level of environmental capital in the former definition and to the weight of environmental quality as compared to the other weights of the arguments in the social welfare function in the latter definition. These weights, and the specification of the welfare function will, in case of the second definition, determine the growth path of environmental quality. More generally, one should clearly distinguish between two subjective or normative elements in this second way of making the concept of sustainable development operational. Firstly, as argued before, this regards the specification of the welfare function and the values of the trade-offs specified in this function. Here the trade-offs between the indicator of environmental quality and the other arguments in the welfare function (e.g. consumption, employment etc.) has to be determined. But obviously such indicator of environmental quality is a composite indicator which is constructed as a weighted sum of indicators of various environmental themes (see e.g. den Butter and van der Eyden, 1998). So the determination of the weights of these theme indicators in the composite indicator of environmental quality has a normative character as well. These weights, and possible non-linearities in the construction of the overall indicator are connected with the definition of sustainability. Yet, after a suitable and feasible set of weights for the theme indicators has been selected, and given the specification and weights of the welfare function, the empirical policy models which are inspired by (and off-springs of) the theoretical models of economic growth can be applied in calculating the conditions for sustainable development.

A look at the literature (see e.g. Daly, 1990, Pearce, Atkinson and Hamilton, 1998 and van den Bergh and Hofkes, 1998) teaches us that at second thought a proper definition of sustainability may prove more complicated than suggested above. It is symptomatic that the Dutch Central Planning Bureau (1996), in a study on the relationship between the economy and the environment, has explicitly refrained from making the concept of sustainability operational in a model based analysis. And the CPB abounds with experience in making policy concepts operational. However, this attitude seems rather lethal and we might as yet try to design scenarios of sustainable development with the help of empirical models. In doing so we should leave the normative element of the definition of sustainability open to policy discussions. Such scenarios may show to the policy maker what policy measures are necessary in order to comply with alternative political interpretations of sustainability and of different trade-offs in the welfare function.

4. An example: a theoretical two sector growth model

As a first example of the integration of the environment in economic models we describe a two-sector endogenous growth model (see Hofkes, 1996). In this two-sector growth model both economic and ecological relationships as well as the interactions between them are fully specified. Furthermore the model incorporates pollution saving technological change and it allows for abatement expenditures. The model distinguishes between a production sector producing a final good and a knowledge or learning sector producing knowledge about an efficient or pollution saving use of environmental resources. The optimal growth rate is determined by maximising a social welfare function in which both economic and environmental values are represented.

The environment enters the model in various ways. First of all the environment plays a role in the production of the final good, both as a stock and as a flow variable. In production on the one hand extractive use is made of the environment (e.g. the use of fossil fuels, but also the polluting effects of carbon emissions resulting from the use of fossil fuels, as the latter also 'harvest' the natural environment) and on the other hand non-extractive use is made of the environment (think for example of the effect of air quality on the health of employees and hence on labour productivity). Furthermore, the environment, also being a consumption good, has a direct impact on human well-being, and as such enters the welfare function.

To avoid that the model becomes too complicated the environment has been build into the model in a highly aggregated way, i.e. only one l-dimensional variable (E) is used. This variable E reflects both the non-extractive, productive services provided at the production side of the economy and the amenity value of the environment at the consumer side of the economy. Furthermore, E represents the stock variable from which the environmental resources used as (extractive) inputs in the production process are drawn. In physical terms E can be thought of as the amount of low entropy (see e.g. Georgescu-Roegen, 1975). The extractive use of environmental resources in production then represents entropic transformation, and extractive use can refer both to the extraction of natural resources and to emissions or the disposal of waste, as both these activities decrease the amount of low entropy. Both forms of extractive use will be called pollution. Natural regeneration, i.e. reproduction of low entropy takes place by solar energy inflow.

It is derived that under certain conditions with respect to production and substitution elasticities, there exists a feasible and optimal sustainable balanced growth path. In other words, under these conditions, there is an optimal growth path on which the economy grows at a constant positive growth rate, keeping environmental quality at a constant level. On this path, growth in technology and abatement activities compensate for the growing use of natural resources in production, such that environmental quality remains constant.

In order to get a better understanding of the mechanisms at work in the model some numerical exercises have been done with the model. By these numerical exercises the influence of changing parameter values on the long-term steady state growth rates for specified production, consumption and regeneration functions can be analysed. It appears, for example, that, under the chosen specification, increased environmental concern lowers the long-term steady state growth rate: abatement activities are increased, while the capital intensity of production increases and environmental quality stabilises at a higher level than in the benchmark. It must be noted that it is theoretically possible to have increasing growth rates under increasing environmental concern in the model. When the impact of the natural environment on production is very large, this can dominate the adverse effect of the negative impact on the absorption capacity of the environment and in this case growth rates can increase if environmental concern increases. A decreased rate of time preference increases long-term growth, while more resources are allocated to the knowledge sector. The outcomes of the numerical exercises, however, just serve as an illustration of the model as more empirical knowledge is needed in particular on the proper specification and parameter values of the regeneration function

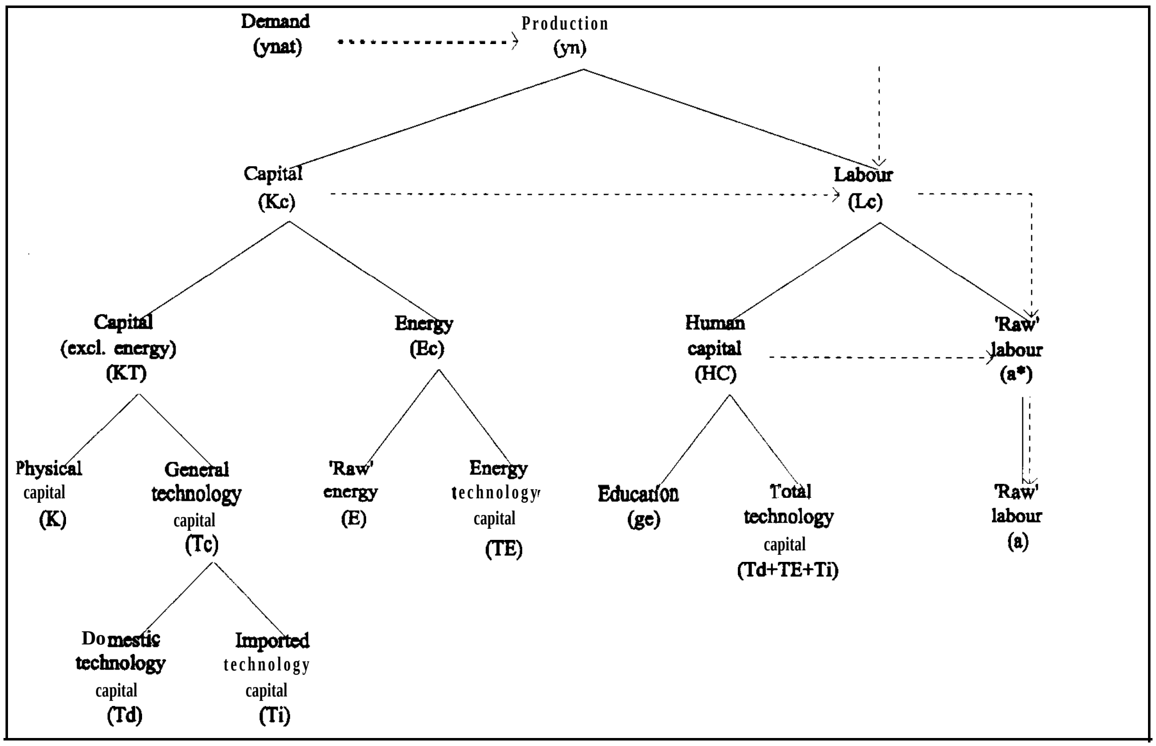
5. An example: the empirical EnTech-model

As a second example of endogenising technical progress and the environment in economic models we illustrate how endogenous growth theory has inspired the construction of a more practical and eclectic dynamic model for policy analysis, namely the EnTech-model (see den Butter, Dellink and Hofkes, 1995, and also den Butter and Wollmer, 1996).

Though the EnTech-model is indeed inspired by some features of endogenous growth theory, it is not an empirical counterpart of these theoretical endogenous growth models. As the model takes the view that prices are rigid and that markets can be in disequilibrium for a prolonged period it intermediates between these formal models and the traditional macro-economic policy models. At the core of the model is the production block, where investments in technology capital and in human capital play a major role. The external effects of R&D are modelled in such a way that R&D investments not only lead to more technology capital, but also have a positive impact on human capital through 'learning by doing' and 'learning by designing'.

In order to capture the main characteristics of the structure of production and the role of technology capital the production block consists of a framework of nested CES-functions, which allows for different elasticities of substitution between the various levels distinguished in the model. Figure 1 shows the structure of the production block. At the highest level of nesting productive capacity, y_n, is a function of efficiency units of capital (including energy), K_c, and labour, L,. L_c refers to efficiency units of labour, L, adjusted for changes in contractual working time. L is determined by the full capacity demand for labour, a^*, and the level of human capital, HC. K_c is determined by efficiency units of capital (excluding energy), K_T, combined with energy, also measured in efficiency units (E_c).

Figure 1 Nested structure of production in the EnTech-model



Technology capital, T_c and (T_d + T_E + T_i), enters into the production block in two related ways. Firstly, firms accumulate knowledge by either undertaking research and development, which provides a domestically produced stock of technical capital, T_d, or they import knowledge, and have a 'substitute' stock of foreign technical capital T,. This technology capital is combined to T_c which may be viewed as being embodied in capital, K, or disembodied and increasing the productivity of existing capital, or both, and thereby it determines the level of efficiency units of capital, K_T. Moreover, in order to endogenise energy saving technology, the model distinguishes between general technology capital and cumulated investments in energy saving technology which enhances the efficiency of the use of energy (T_E). Therefore, energy saving technology capital combined with input of 'raw' energy (E) yields efficiency units of energy (E_c).

A major feature of the model which is indeed in line with endogenous growth theory is that it is assumed that there are spill-overs of knowledge associated with research and development and the import of technical capital. This is considered to augment the human capital of workers as they work with the new technologies, *i.e.* through 'learning-by-doing' and 'learning-by-designing'. This augmentation of human capital combines, in a complementary manner, with the education level of workers, which is itself determined by real government expenditures on education, g_e. It should be noted that this version of the EnTech-model still assumes a constant returns technology. However, in a sensitivity analysis den Butter and Wolhner (1996) investigated a version of the model where it is assumed that spill-overs enter the aggregate production function at the highest level of nesting. Then, given constant returns to the 'normal' production factors there is increasing returns to all factors. This alternative version of the model is still further in line with the notion of endogenous growth theory on the non-rival character of technology capital.

When all factor inputs (including labour supply) were either determined by factor demand functions or exogenously given, y_n would be endogenously determined by the production block. Hence 'causality' would run from the lower elements in the tree of Figure 1 (indicated by solid lines) to the highest hierarchical level where y_n is the final variable to be determined. However, when productive capacity is demand determined, labour demand, a, follows as a residual; then 'causality' runs from the left to the right in Figure 1 (indicated by broken lines).

The EnTech-model is, amongst others, used to simulate the effects of the introduction of regulating energy levy. These simulation experiments show that an energy levy of 50% may, in the short and medium term, generate an employment double dividend. A decrease in the wedge between labour costs borne by the employer and the net income received by the employee induces substitution effects to labour. These substitution effects appear to be enhanced by the explicit modelling of technology spill-overs to labour. The simulation experiments consider various alternative assumptions with respect to the level of the levy (a general levy or a levy that effects of private households only) and to the way the proceeds of the levy are redistributed. An alternative considered in one of the simulation experiments is to use part of the proceeds for additional investments in R&D on energy saving technology. As noted above, it appears that the spill-overs from technology capital to human capital, which represent the positive externalities of R&D investments, are important for the impact of an energy levy on employment. Hence this model exercise shows that the size of these positive externalities due to the spill-overs plays a major role in the discussion on the double dividend hypothesis (see the next section).

However, the outcomes of the potential simulations also appear to be quite sensitive to the way the goods and labour markets are modelled. It is especially true for the calculated effects of an autonomous impulse in R&D investments on employment. The effect may be either positive or negative depending on the specification of the model. This is also illustrated by a research project of van Bergeijk *et* al. (1995), who have built a production block with a similar structure of that of the EnTech-model with spill-overs to human capital into a calibrated applied general equilibrium model of the Dutch economy.

6. Endogenous technology and environmental policy

The models discussed in the previous sections, which endogenise technology and economic growth, provide a framework for the analysis of policy measures which are directed at sustainable economic development. As environmental policy aims to be effective especially in the long run, it will unavoidably induce structural changes in economic activities in general, and in production in particular. As we have seen in the models of the previous sections, technical progress is a major determinant of economic growth. Therefore it is crucial for environmental policy to try to influence technical progress and the bias of that technical progress.

For a better understanding of how environmental policy can provide incentives for a reduction of the use of environmental capital in the production process, this section discusses some relevant aspects of the relationship between technological innovation, economic growth and productivity growth. Traditional economic theory focuses on two production factors, namely labour and capital. In this stylised model of the production process technical progress will lead to an increase in total factor productivity (TFP). It implies that with a gradual increase in technology at present the same product volume can be produced with less input of capital and labour than in the past. Or, similarly, that with the same inputs of production factors from the past, the present volume of production will be higher. Such increase of total factor productivity due to technical progress can materialise in the production process in different ways. One possibility is that for the same volume of production the same input of capital is needed as in the past, but that the input of labour can be reduced. In that case *we have labour saving technical process* which leads to an increase in labour productivity which is equal to the increase in total factor productivity. Then the productivity of capital remains the same. The mirror image of this case occurs when the same amount of labour but less capital is needed in order to produce the same amount as before. This is *the* case of *capital saving technical progress.* This latter case illustrates that an increase in total factor productivity due to technological progress does not necessarily imply an increase in labour productivity.

On the other hand, an increase in labour productivity is not a necessary consequence of total factor productivity growth due to technical progress. When a number of alternative techniques is available for production where, more formally stated, the production function allows for substitution between the production factors, a relative increase in the price of labour (wage costs) - or, the other way around, a relative decrease in the price of capital - will imply an input of less labour and of more capital for producing the same amount of products. In that case the increase in labour productivity is merely the consequence of substitution from labour to capital because of a change in relative factor prices.

Apart from this direct substitution effect a relative change in factor prices also has its influence on the input of production factors because it will affect *the bias* of technological change. For instance, when the relative price of labour increases with respect to that of capital, investments in the development of new technology will be directed more towards the development of labour saving technology than before. It implies that, given total factor productivity, the structure of production will become more labour saving than in the case of no change in relative factor prices. The additional growth of labour productivity due to the change in the bias of technical progress will come in surplus of the growth of labour productivity which is the result of the substitution effect because of the change in relative factor prices.

When, as in the models of the previous sections, besides capital and labour, the environment is included as an additional production factor, a similar, albeit somewhat more complicated argumentation holds. An increase in total factor productivity due to the implementation of a new technology may either result in a growth of labour productivity, in a decrease of the input of capital per unit of production and/or in a phenomenon which can be named the *growth of environmental productivity.* In this case the growth of environmental productivity is equal to the decrease in the environmental intensity of the production process. When technical progress has an environment saving character it implies that the environmental productivity - which is often labelled as environmental efficiency - increases.

In a similar way as in the previous case of two production factors a relative change of factor prices will also result in a combination of various effects when we distinguish between three factors of production. When, e.g. a spontaneous or policy induced increase in the price of the environment occurs, this will, in case of sufficient possibilities for substitution, lead to a decrease in the input of the environment as production factor and to an increase in the input of both other factors of production. Hence, because of this substitution effect environmental productivity will increase and consequently the labour productivity and/or the capital productivity will decrease. An increase in an environmental productivity, or in environmental efficiency, is therefore not necessarily a consequence of application of a new environment saving technology. However, yet another mechanism will play a role in this case. Because of the relative change in factor prices more attention will be paid to the development of environment saving techniques at the expense of the development of capital saving or labour saving techniques. This is a second reason why a higher price of the environment will eventually lead to an increase in environmental efficiency, and to a relative decrease in labour productivity and/or capital productivity as compared to a scenario without relative price changes.

The previous argumentation shows that apparently the process of structural change, which is a result of technological innovation, has many faces, which, amongst others, depend upon the development of relative prices of the production factors. However, in practice it is impossible to adapt the production method immediately to changes in factor prices. An important reason is that techniques are incorporated in existing capital goods. These capital goods should be used in the production process for a considerable period of time in order to have the investment costs earned back. New capital goods cannot be installed solely because more efficient techniques have become available or because changes have occurred in relative prices of production factors. Apart from an informational deficiency of the producer, this phenomenon of 'time to build - or to restructure - may be a reason why in case of so called win-win situations, whereby implementing new techniques, because of which the production process can be both more environment saving and more labour saving, such new technology is not always immediately installed. Moreover, it takes time (and money) to instruct the personnel and let it become familiar with the working of the new technology. However, indirectly and in due time, a change in relatively prices will indeed lead to a change in the structure of production where the bias of technical progress is directed to that production factor which has become relatively more expensive.

Suppose e.g. that technical progress is neutral with respect to the production factor capital which implies a constant capital output ratio. With high wage costs and a low price for the use of the environment, technological innovation will be directed at labour saving techniques. Moreover, when wage costs rise, the focus will be on scrapping of labour intensive capital goods. On the other hand, when the increase in the costs of the environment exceeds the rise in wage costs, e.g. as a result of policy measures, the entrepreneurs will select those new production techniques from the range of possible techniques which yield the highest environmental efficiency. Moreover, when selecting old capital goods which are to be scrapped, the use that the production process makes of the environment will have a larger weight in the decision to scrap than labour intensity.

We may think of a vintage approach with two technological dimensions. In that case both the selection criterion for the production technology of new vintages and the scrapping condition of the old vintages depends on, at the one hand, the difference between total factor productivity and the weighted average price increases of environment and labour as production factors, and, on the other hand, on relative prices with respect to these two production factors. Obviously only model based calculations can show which will be the net result with respect to labour saving and environment saving in case of chances of factor prices.

What implications do these mechanisms have for environmental policy which aims at the reduction of the use of environmental capital and which therefore has to be directed at an increase of environmental productivity? Given the available funds for research and development, so that, roughly speaking total factor productivity remains the same, such policy leads to a relative decrease in labour productivity and/or capital productivity in comparison with the scenario without environmental policy. These changes in productivity will also lead to changes in product prices for different products. It implies that environment intensive, 'dirty' products will become more expensive relative to 'clean' products which use less environment in the production process. This is because, in general, possibilities for substitution in the production process will be too small to fully compensate the changes in factor prices.

Hence, in general the products of sectors of industry with environment using production methods will become more expensive in comparison to products from sectors which use a clean technology. So, to some extent, the aim of the policy, namely a decrease of the use of the environment as production factor as compared with the trend scenario, will be reached by means of a relative shrinking of the environment using sectors and a relative growth of the clean sectors. This can be seen as a consequence of a general policy which is directed at intemalising the negative externalities of the use of environment in production. Therefore, in order to achieve a shift in the sectoral structure of production which leads to less damage to the environment, there is no need for environmental policy to take specific measures with respect to dirty sectors of industry.

To what shifts between sectors of industry will such general policy of enhancing the price of the environment lead? There are three arguments why these shifts may be less substantial than one would expect before hand. Firstly, empirical evidence on job destruction and job creation shows that restructuring within sectors of industries and regions is very large as compared to restructuring between sectors and regions (see e.g. Davis, Haltiwanger and Schuh, 1996). This apparent heterogeneity of firms within sectors implies that environmental policy will induce a growth of those firms within the sectors which already applied environment saving technologies. Secondly, environmental costs will be increasingly important in the scrapping criterion of old capital goods as compared to labour costs. It implies that environmental policy will induce an increase of environmental productivity within each sector of industry. An additional implication is that research and development will be directed more towards environmental saving techniques, which materialises mainly in the long run. Then, in the process of gradual renewal of vintages of production goods which goes along with technical progress, more environment saving production methods will be installed than would have been the case without environmental policy.

Thirdly, the fact that dirty goods become more expensive does not necessarily imply that the production sectors which produce those dirty goods will decrease in proportion to the relative price increase of the dirty goods. This is very much dependent upon the price elasticity of the dirty goods. When the price elasticity is low, the share of those dirty goods in total demand will increase in money terms and shifts between sectors will be less than proportional to price changes. We note that, when the ensuing changes in the composition of the value of demand are unwarranted, environmental policy can also be directed at influencing preferences.

7. Conclusions

In this article we have considered the integration of the environment in economic models. As environmental developments usually take place on a rather long time scale, it is best to integrate the environment in economic models which also focus on long-term developments. In studying the long term relation between economy and ecology, (the development of new) technology plays an important role. From this perspective we have considered a theoretical endogenous growth model, which incorporates pollution saving technological change and an empirical model based on the theory of endogenous growth, in which technological development also plays an important role.

Both models considered, provide a framework for the analysis of the effects of environmental policies. The main conclusion that can be drawn is that environmental policies, that cause a relative change in factor prices, will not only influence environmental productivity through the substitution effect, but can also influence the bias of technological change. Through this effect on the bias of technological change, environmental policies will ultimately also influence the process of structural change which is, *a.o.*, a result of technological innovation. However, in practice, considerable shifts in sectoral composition will not take place immediately and may be less substantial than one would expect beforehand. Our scope for future research is to construct a comprehensive model that will enable us to disentangle all of these interacting influences of environmental policy on the structure of production and consumption.

References

Bergeijk, P.A.G. van, M.A. van Dijk, R.C.G. Haffner, G.H.A. van Hagen, R.A. de Mooij and P.M.Waasdorp, 1995, *Economic Policy, Technology and Growth,* Beleidsstudies Technologie Economie, 30, Ministry of Economic Affaurs, The Hague.

Bergh, J.C.J.M. van den and M.W. Hofkes, 1998. A Survey of Economic Modelling of Sustainable Development, in: J.C.J.M. *van* den Bergh and M.W. Hofkes (eds.), *Theory and Implementation of Economic Models for Sustainable Development,* Kluwer Academic Publishers, Dordrecht.

Bovenberg, A.L. and S. Smulders, 1995, Environmental Quality and Pollution Saving Technological Change in a Two-sector Endogenous Growth Model, *Journal of Public Economics, 57,* pp. 369-391.

Butter, F.A.G. den, R.B. Dellink and M.W. Hofkes, 1995, Energy Levies and Endogenous Technology in an Empirical Simulation Model for the Netherlands, in: A.L. Bovenberg and S. Cnossen (eds.), *Public Economics and the Environment in an Imperfect World,* Kluwer Academic Publishers, Boston, pp. 3 15-335.

Butter, F.A.G. den, and J.A.C. van der Eyden, 1998, A pilot index for environmental policy in The Netherlands, *Energy Policy, 26,* pp. 95-101.

Butter, F.A.G. den, and F.J. Wollmer, 1996, An empirical model for endogenous technology in The Netherlands, *Economic Modelling,* 13, pp. 15-40.

Centraal PlanBureau (CPB), 1996, *Economie en Milieu; op Zoek naar Duurzaamheid.* Sdu Uitgevers Den Haag.

Daly, H.E., 1990, Toward some Operational Principles of Sustainable Development, *Ecological Economics, 2,* pp. 1-6.

Davis, S.J., J.C. Haltiwanger and S. Schuh, 1996, *Job Creation and Destruction,* MIT Press, Cambridge, Mass..

Forster, B.A., 1973, Optimal Capital Accumulation in a Polluted Environment, *Southern Economic Journal, 39,* pp. 544-547.

Georgescu-Roegen, N., 1975, Energy and Economic Myths, *Southern Economic Journal,* 41, pp. 347-381.

Gradus, R. and S. Smulders 1993, The Trade-off between Environmental Care and Long-Term Growth: pollution in three prototype growth models, forthcoming *in Journal of Economics.*

Gruver, G., 1976, Optimal Investment and Pollution Control in a Neoclassical Growth Context, *Journal of Environmental Economics and Management, 5,* pp. 165- 177.

Hofkes, M.W., 1996, Modelling Sustainable Development: an economy-ecology integrated model, *Economic Modelling*, 13, pp.333-353.

Lucas, R.E., 1988, On the Mechanisms of Economic Development, *Journal of Monetary Economics, 22,* pp. 3-42.

Pearce, D., G. Atkinson and K. Hamilton, 1998, The Measurement of Sustainable Development, in: J.C.J.M. van den Bergh and M.W. Hofkes (eds.), *Theory and Implementation of Economic Models for Sustainable Development,* Kluwer Academic Publishers, Dordrecht.

Rebelo, S., 199 1, Long-Run Policy Analysis and Long-Run Growth, *Journal of Political Economy, 99, pp. 500-52* 1.

Romer, P.M., 1986, Increasing Returns and Long-run Growth, *Journal of Political Economy, 94,* pp. 1002-1037.

Solow, R., 1956, A Contribution to the Theory of Economic Growth, *Quarterly Journal of Economics, 70,* pp. 65-94.

Solow, R., 1957, Technical Change and the Aggregate Production Function, *Review of Economics and Statistics, 39,* pp. 3 12-320.

Solow, R.M., 1974, The Economics of Recources or the Recources of Economics, *American Economic Review, 64,* pp. 1-14.

Stiglitz, J., 1974, Growth with Exhaustible Natural Resources: efficient and optimal growth paths, *Review of Economic Studies,* Symposium, pp. 123-127.

Swan, T.W., 1956, Economic Growth and Capital Accumulation, *Economic Record, 32,* pp. 343-361.